

Influence of the single particle Zeeman energy on the quantum Hall ferromagnet at high filling factors

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In a recent paper [Phys.Rev.B.**72**,245325(2005)], we have shown that the lifting of the electron spin degeneracy in the integer quantum Hall effect at high filling factors should be interpreted as a magnetic-field-induced Stoner transition. In this work we extend the analysis to investigate the influence of the single particle Zeeman energy on the quantum Hall ferromagnet at high filling factors. The single particle Zeeman energy is tuned through the application of an additional in-plane magnetic field. Both the evolution of the spin polarization of the system and the critical magnetic field for spin splitting are well-described as a function of the tilt angle of the sample in the magnetic field.

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The integer quantum Hall effect has historically been described within the framework of a single electron picture. Electron-electron interactions are then introduced as a correction, leading to enhanced spin gaps at odd filling factors. Clearly, from a perturbation theory point of view, this approach is wrong, at least for the most widely investigated GaAs system, for which the energy scale of the electron-electron interactions ($e^2/4\pi\epsilon\ell_B$) is more than an order of magnitude larger than the single particle Zeeman energy ($g^*\mu_BB$). At high magnetic field (low filling factors), this has wide ranging consequences, with the observation of the itinerant quantum Hall ferromagnet,¹ with spin wave² or spin texture excitations³ at filling factor $\nu = 1$.

The *collapse* of spin splitting at low magnetic fields (high filling factors) has been investigated experimentally^{4,5,6} and theoretically.⁷ Leadley and co-workers⁶ showed that the critical filling factor for the *collapse* of spin splitting is found to increase with increasing tilt angle. The Zeeman energy, greatly enhanced at high tilt angles, favors the transition to a polarized state. This latter point is theoretically supported by the pioneering work of Fogler and Shklovskii,⁷ who proposed an order parameter, $\delta\nu$, to quantitatively characterize the *collapse* of spin splitting. This order parameter corresponds to the filling factor difference between two consecutive resistance maxima in $R_{xx}(B)$, related to spin up and down sub-levels associated with a given Landau level. In the Fogler and Shklovskii model, the spin splitting ($\delta\nu$) collapses, when the disorder broadening of the Landau levels is comparable to the exchange enhanced spin gap.

In an equivalent, but intuitively different approach, we

have recently shown⁸ that the *appearance* of spin splitting results from a competition between the disorder induced energy cost of flipping spins and the exchange energy gain associated with the polarized state. In this case the Zeeman energy plays no role, and the only effect of the magnetic field is to modify the density of states at the Fermi energy, essentially through the Landau level degeneracy eB/h . Here, we use the experimental behavior of the order parameter $\delta\nu$ to probe the appearance of spin splitting in $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ heterojunction (HJ) and quantum well (QW) structures. A large in-plane magnetic field is used to tune (enhance) the single particle Zeeman energy by more than an order of magnitude. Experimentally this is achieved by rotating the sample in the magnetic field. We show that the behavior of the spin polarization as a function of the tilt angle can be quantitatively described within the framework of our previously developed approach for the appearance of spin splitting, with no free parameters.⁸

We briefly recall our simple model for the appearance of spin splitting in the highest occupied Landau level before introducing the effect of a non-zero Zeeman energy. In the limit of a zero Zeeman energy, we consider an unpolarized initial state in the N^{th} Landau level, with a total number of electrons $n_{\text{tot}} = eB/h$. In this situation the Fermi level E_F lies in the center of the degenerate spin up and down sub-levels and the filling factor of the system is odd. The development of a non-zero spin polarization requires that the “disorder” energy cost of populating higher energy levels by flipping spin should be less than the gain in exchange energy stabilizing the newly polarized state. The energy cost of flipping spin is

inversely proportional to the density of states of one spin sub-level at Fermi level $D(E_F)$, and it can be shown⁸ that it will be energetically favorable for spins to flip when:

$$\frac{1}{D(E_F)} = X, \quad (1)$$

where X is the exchange energy between two spins, essentially depending only on the electron density n_s . This condition is nothing other than the well-known Stoner condition for ferromagnetism in metals.⁹

In the presence of a non-zero Zeeman energy, there is an initial spin polarization of the system at odd filling factors. To include this effect, one has to consider the global spin polarization, m , in Landau level N , resulting from the total spin gap induced by exchange and Zeeman energies. The latter can then be written,

$$\Delta_s = |g^*| \mu_B B + X m n_{tot}, \quad (2)$$

where g^* is the effective bare g-factor and $n_{tot} = eB/h$ and m are the occupancy and the spin polarization of the N^{th} Landau level respectively. Here $m n_{tot}$ corresponds to the difference between the number of spin up and spin down electrons which is at the origin of the exchange gap. For simplicity we define the zero of energy to be at the Fermi level ($E_F \equiv 0$). The spin polarization $m = (n_\uparrow - n_\downarrow)/n_{tot}$ resulting from the spin gap Δ_s can then be written,

$$m = \frac{1}{n_{tot}} \int_{-\infty}^0 \left[D\left(E + \frac{\Delta_s}{2}\right) - D\left(E - \frac{\Delta_s}{2}\right) \right] dE, \quad (3)$$

where $D(x) = (1/\Gamma\sqrt{\pi}) \exp(-x^2/\Gamma^2)$ for Gaussian broadened Landau levels of width Γ . Eqs.(2) and (3) need to be solved self-consistently to find m and Δ_s and are essentially equivalent to the solution proposed by Fogler and Shklovskii.⁷ For Gaussian Landau levels,

$$m = \text{erf}\left(\frac{1}{2} \frac{(|g^*|\mu_B B + X m n_{tot})}{\Gamma}\right), \quad (4)$$

where $\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$. We note that assuming an energy independent density of states around E_F (equivalent to assuming a “rectangular” Landau level) we obtain,

$$m = \frac{(|g^*|\mu_B B + X m n_{tot})D(E_F)}{n_{tot}}. \quad (5)$$

However, this is only a good approximation for small values of m , so the equation required to express the continuous evolution of the spin polarization as a function of the magnetic field is Eq.(4). Fogler and Shklovskii⁷ have shown that there is a simple relation, $m = \delta\nu$, linking the polarization and the filling factor separation of the peaks in $R_{xx}(B)$, which allows a direct comparison of theory with experiment. In Fig. (1) we plot the magnetoresistance $R_{xx}(B)$ and measured $\delta\nu$ for sample NRC0050 (the sample parameters are summarized in Table I). The evolution of $m(B)$ calculated using Eq.(4) with $g^* = -0.44$, the generally accepted value for bulk GaAs,¹⁰ and $g^* = 0$,

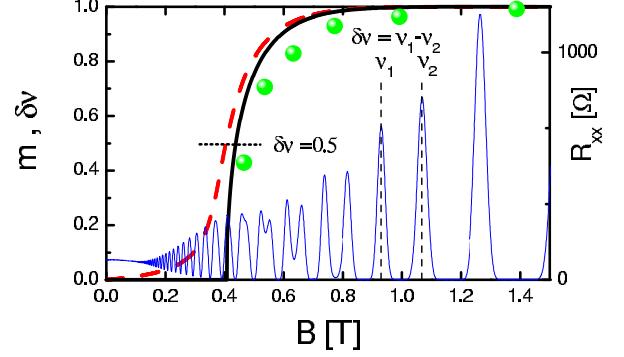


FIG. 1: (color on-line) $R_{xx}(B)$ measured at $T = 50$ mK for sample NRC0050. The experimentally determined $\delta\nu$ are also plotted (closed circles). The evolution of the spin polarization $m(B)$ calculated using Eq.(4) in the presence of a Zeeman energy ($g^* = -0.44$) (dashed line), and without Zeeman energy ($g^* = 0$) (thick solid line) are also shown. The condition $\delta\nu = 0.5$ used to estimate B_{ss} is indicated by the dotted horizontal line.

are also plotted in Fig.1. The values used for Γ and X used in the calculation have been independently determined for this sample as explained in Ref. [8].

Eq.(4) reproduces extremely well the collapse of the spin polarization observed in $\delta\nu$, especially considering that there are no fitting parameters. The effect of a non-zero Zeeman energy is similar to the one obtained in Ref. [7], shifting the phase transition to lower magnetic field. To evaluate quantitatively the Zeeman correction, we define a critical magnetic field, B_{ss} , corresponding to a value of $\delta\nu = 0.5$, as already proposed in Refs. [6] and [7]. B_{ss} can be extracted from the model by putting $m = \delta\nu = 0.5$ into Eq.(4), with and without the Zeeman correction. The difference between these two results is at most $\sim 10\%$ for $g^* = -0.44$, undiscernible within experimental error, confirming the negligible role of the Zeeman energy in the perpendicular configuration.

It is however possible to increase the Zeeman energy by applying a strong in-plane magnetic field. Experimentally this can be achieved by rotating the sample away from the B normal to the 2D electron gas configuration. The Zeeman energy depends on the total magnetic field B , in contrast to orbital effects such as the Landau level degeneracy or the cyclotron energy which are only sensitive to the B_\perp component of the field. Hence rotation can be used to tune the Zeeman energy. For a given perpendicular magnetic field B_\perp , the strength of the Zeeman energy can be increased by orders of magnitude at high

TABLE I: Parameters of the samples investigated.

Sample	n_s (cm^{-2})	Γ (K)	Structure	g^*
NRC0050	1.7×10^{11}	1.8 ± 0.1	HJ	-0.44
LPN06	4.0×10^{11}	3.9 ± 0.6	HJ	-0.44
NU1783b	1.8×10^{11}	1.8 ± 0.2	HJ	-0.44
F1200	7.6×10^{11}	1.7 ± 0.1	QW	-0.1

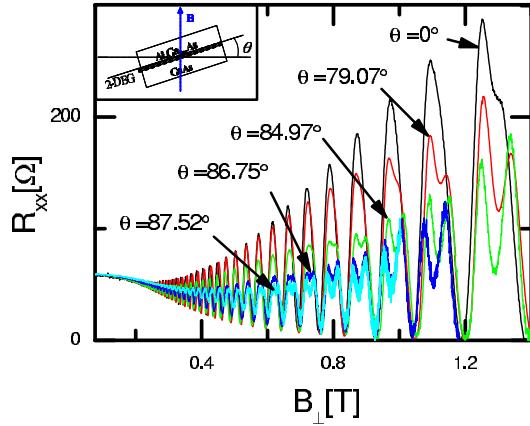


FIG. 2: (color on-line) $R_{xx}(B_\perp)$ for sample *LPN06* measured at $T = 30$ mK for different tilt angles (θ).

tilt angles. We therefore expect that rotating the sample should provide an incisive test of the zero free parameter model developed to predict the appearance of spin splitting in Ref. [8].

The effect of the increased single particle Zeeman gap is clearly visible in Fig. 2, in which plot $R_{xx}(B_\perp)$ measured at $T = 30$ mK for a GaAs heterojunction at various tilt angles (θ). $R_{xx}(B_\perp)$ was measured using a standard low frequency lock-in technique under magnetic fields up to $23T$ in a dilution fridge equipped with an *in-situ* rotating sample holder. As the tilt angle is increased, for a given B_\perp , the minima at odd filling factor strengthen, reflecting the increase of the spin gap. This effect can also be seen in the behavior of $\delta\nu$ as a function of B_\perp (extracted from $R_{xx}(B_\perp)$), for different tilt angles, plotted for a GaAs heterojunction in Fig.3. The appearance of spin splitting is clearly shifted to lower B_\perp with increasing Zeeman energy at high tilt angles. Tilting the sample increases the Zeeman energy without affecting either the disorder or the exchange parameter. This is quite clear from Eq.(4) where the total magnetic field only enters through the Zeeman term, with n_{tot} involving only the perpendicular component. A similar approach was first proposed in Ref. [6] to extract the enhanced g-factor from the coincidence method at high tilt angles. Practically, Eq.(4) can in this case be written,

$$m = \text{erf} \left(\frac{1}{2\Gamma} \left(|g^*| \mu_B \frac{B_\perp}{\cos(\theta)} + X m \frac{eB_\perp}{h} \right) \right). \quad (6)$$

The predicted behavior is shown in Fig.3, calculated using Eq.(6), with the parameters Γ and $X(n_s)$, determined from an analysis of the oscillations in $R_{xx}(B)$ before spin splitting occurs, and, the calculations of Attacalite et al.,¹¹ respectively, as detailed in Ref. [8]. We impose here the generally accepted value of $g^* = -0.44$ for bulk GaAs. The effect of an increasing tilt angle on the collapse of $\delta\nu$ is well reproduced, considering the slight discrepancy between our model and experiment in the perpendicular configuration (see the curve for $\theta = 0^\circ$ and

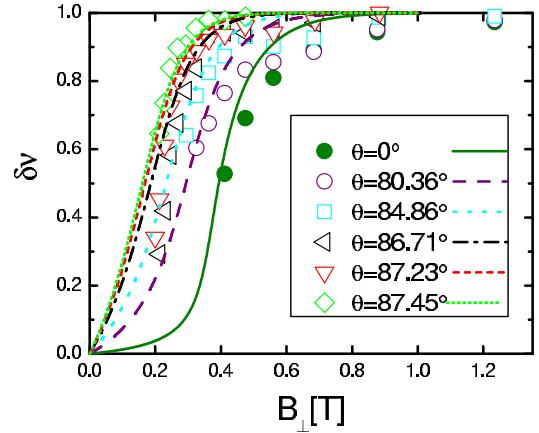


FIG. 3: (color on-line) Parameter $\delta\nu(B_\perp)$ for sample *NU1783b*, extracted from measured $R_{xx}(B)$ at $T = 50mK$, for different tilt angles (symbols). Spin polarization m calculated using Eq.(6) (solid and broken lines).

the data associated (full circles)). We stress that there are no free fitting parameters in our model which nevertheless provides a good quantitative description. For high tilt angles, the experimental collapse of $\delta\nu$ seems more pronounced than the predicted variation and a possible reason for this is proposed later.

It is important to mention here that the self consistent nature of Eq. (6), which arises from the dependence of the exchange gap on the spin polarization, is essential in obtaining such good agreement. The reason for this is that even at fixed perpendicular magnetic field, the spin polarization at odd filling factor can be modified due to the change in the single particle Zeeman energy, if the spin Landau levels overlap, leading to a modification of the exchange gap.

We now turn to the evolution of the critical magnetic field B_{ss} with tilt angle. From the curves of Fig.3 we can extract the experimental magnetic field B_{ss} corresponding to the condition $\delta\nu = 0.5$. This quantity is shown for the 3 samples for which we have rotation data in Fig.4 as a function of the tilt angle θ . *LPN06* and *NU1783b* are the two GaAs heterojunction already presented and *F1200* is a 13nm wide GaAs quantum well. In order to focus only on the effect of tilting, we plot the value $B_{ss}(\theta)$ normalized by its value in the perpendicular configuration, $B_{ss}(0)$. As expected, $B_{ss}(\theta)/B_{ss}(0)$ is greatly reduced at high tilt angles, when the Zeeman energy is increased by over an order of magnitude. Reductions of more than 50% are observed for angles approaching 90° . From a self-consistent solution of Eq.(6) we can obtain the predicted magnetic field B_{ss} as a function of the angle θ . As B_{ss} corresponds to the condition $\delta\nu = 0.5$, the solution is obtained setting $m = 0.5$ in Eq.(6). The predicted evolution of $B_{ss}(\theta)/B_{ss}(0)$ is plotted, as solid and broken lines, for the three samples in Fig.4(a).

As before, Γ and X have been independently determined for each sample.⁸ For the heterojunction sam-

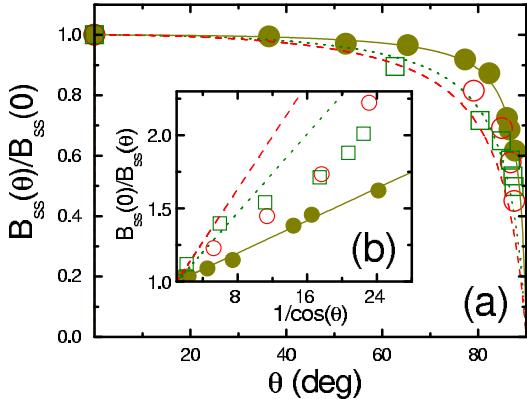


FIG. 4: (color on-line) (a) $B_{ss}(\theta)/B_{ss}(0)$ as a function of θ for 3 different samples at $T = 50$ mK: *F1200* (full circles), *NU1783b* (open squares) and *LPN06* (open circles). Self-consistent solutions of Eq.(6), for the three samples, are also plotted (lines). (b) $B_{ss}(0)/B_{ss}(\theta)$ as a function of $1/\cos(\theta)$ for the three samples (symbols) together with the predictions of Eq.(6) (lines).

ples, *NU1783b* and *LPN06*, good agreements with the data are obtained using the generally accepted value of $g^* = -0.44$ for bulk GaAs.¹⁰ For the 13nm quantum well sample, *F1200*, we expect a significantly lower value for the bare g-factor owing to the confinement energy and the penetration of the wave function into the barriers.¹² In addition, non-parabolicity is expected to further reduce the g-factor¹³ as the electronic density (Fermi energy) is in this sample quite high ($n_s = 7.5 \times 10^{11} cm^{-2}$). A good agreement with the data can be obtained using $g^* = -0.1$ which is not unreasonable.

As can be seen in Fig.4(a) a generally good quantitative agreement is obtained confirming the relevance of the physical approach proposed. A slight discrepancy ($\sim 20 - 30\%$) is observed at large angles for samples *NU1783b* and *LPN06* between the prediction and the experimental B_{ss} , the latter being slightly larger. This can be seen in Fig.4(b) in which we plot the experimental and predicted $B_{ss}(0)/B_{ss}(\theta)$ as a function of $1/\cos(\theta)$. Intuitively, the linear dependence, observed for

the exact numerical solution of Eq.(6), can be understood from the approximate expression for m in Eq.(5), writing $B = B_\perp / \cos(\theta)$, $D(E_F) = eB_\perp/h\Gamma\sqrt{(\pi)}$, $n_{tot} = eB_\perp/h$, and $m = 0.5$ which gives,

$$\frac{B_{ss}(0)}{B_{ss}(\theta)} \approx \frac{1}{\cos(\theta)} \left(\frac{g^*\mu_B}{g^*\mu_B + Xe/2h} \right) + \left(\frac{Xe/2h}{g^*\mu_B + Xe/2h} \right)$$

This expression provides a reasonable prediction for the slope of the $1/\cos(\theta)$ dependence, for decreases in $B_{ss}(\theta)$ of less than $\sim 50\%$. A deviation from theory is clearly visible at large θ (large $1/\cos(\theta)$) for samples *NU1783b* and *LPN06*. For *F1200* however a linear behavior in good agreement with the prediction is observed. A possible explanation for these discrepancies is that the large in-plane magnetic field, at large tilt angles, increases the Landau level width, which would shift the appearance of spin splitting to higher perpendicular magnetic field. At large tilt angles, the amplitude of the oscillations in $R_{xx}(B_\perp)$ decrease significantly for a given B_\perp (see Fig.2), revealing a modification of the scattering as the in-plane magnetic field increases. The effect of the in-plane magnetic field, which we have also observed in in-plane magnetoresistance measurements ($\theta = 90^\circ$), is in GaAs a complex interplay between spin and orbital effects^{14,15} affecting both the quantum lifetime (Landau level width) and the effective mass. The orbital part of this effect is weaker in quantum wells in which the spacing between electronic subbands is larger than in heterojunctions, limiting the inter-subband transitions induced by an in-plane magnetic field. This would be consistent with the fact that sample *F1200*, a 13nm quantum well, is not affected by this process and shows no deviation from the predicted linear behavior.

In summary, we have extended our model for the quantum Hall ferromagnet at high filling factors to the case of a non-zero Zeeman energy. The Zeeman energy has been tuned via tilted field measurements. Our simple model, with no free fitting parameters, provides a reasonable quantitative description of the Zeeman energy dependence of spin polarization (spin splitting) at odd filling factors.

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